

# **THREE-DIMENSIONAL FLOW-THROUGH ELECTRODE AND ELECTROCHEMICAL CELL**

## **CROSS-REFERENCE TO RELATED APPLICATIONS**

This application claims priority of U.S. Provisional Patent Application Serial No.

5 60/450,891 which was filed on February 28, 2003, entitled "THREE-DIMENSIONAL FLOW-  
THROUGH ELECTRODE AND ELECTROCHEMICAL CELL." The entire disclosure of the  
provisional application is considered to be part of the disclosure of the accompanying  
application, and is hereby incorporated by reference in its entirety.

## **TECHNICAL FIELD**

10 The present invention relates to electrodes and, more specifically, to the use of three-  
dimensional flow-through electrode and electromechanical cells used for a number of  
applications, including water purification, improving crop yields, metal processing, chemical  
manufacturing and environmental cleanup.

## **BACKGROUND OF THE INVENTION**

15 Electrolytic processes are commonly conducted using planar electrodes. Electrodes are  
well known in the art and include a conductor which is in contact with a plate, in which various  
types of solutions flow-by the electrode. A number of specific electrodes have been designed in  
20 which the solutions flow-through one or more electrodes. These electrodes have been made from  
a variety of materials and material shapes. One problem addressed by the present invention  
relates to the method of feeding electrical current into an electrode; specifically into a three-  
dimensional electrode composed of graphite felt material which provides a large surface area for  
electro-chemical reactions.

Previously used graphite felt electrodes typically feed electrical current through contact of a conductor metal either on the edges of a thin graphite felt electrode, as disclosed, for example, in U.S. Patent No. 6,342,150 to Sale et al., issued on January 24, 2002 and entitled "Redox water treatment system," and U.S. Patent No. 5,376,240 to Kaczur et al., issued on December 27, 1994 and entitled "Process for the removal of oxynitrogen species for aqueous solutions," both of which are incorporated herein by reference in their entirety. Other previously used graphite felt electrodes feed current through a metal in planar contact with a thin graphite felt electrode as disclosed, for example, in U.S. Patent No. 6,086,733 to Carey et al., issued on July 11, 2000 and entitled "Electrochemical cell for metal recovery," or through a metal back-plate in planar contact with a thicker graphite felt electrode as disclosed in previously mentioned U.S. Patent No. 5,376,240, both of which are incorporated herein by reference in their entirety. Still other known graphite felt electrodes feed current by inducing an electrical charge in a thicker graphite felt electrode by inserting it between two oppositely charged electrodes so the graphite felt becomes bi-polar with regard to electrical charge. Such an electrode is disclosed in U.S. Patent No. 5,744,028 to Goto et al., issued on April 28, 1998 entitled "Water treating apparatus," which is also incorporated herein by reference in its entirety. All of these methods work to some degree for their specific intended purpose; unfortunately, they all fail in their ability to handle significant current flows.

Accordingly, it would be advantageous to have an electrode which is relatively large, which can provide a large surface area for efficient chemical reactions which can be used in water purification, metal processing, chemical manufacturing and environmental cleanup, to

name a few possible applications. Furthermore, it would be advantageous for such an electrode to be capable of handling relatively large current flows.

## SUMMARY OF THE INVENTION

5           The present invention solves the aforementioned problems and meets the aforementioned needs, and other needs. In one embodiment, an efficient method is provided for feeding current into a three-dimensional, flow-through electrode preferably utilizing a graphite felt material. Rods of a conducting material, preferably graphite, are inserted at predetermined spacing into a block of graphite felt electrode as current feeders. The spacing of these conductor materials  
10 throughout the graphite felt block allows for efficient current distribution despite the electrical resistance of the graphite. The large surface area provided by the graphite felt makes it possible to expose solutions or gases to electrical charges instituting electrochemical reactions. This large surface area, providing approximately 17,000 square feet of graphite surface for each cubic foot of graphite felt, makes it possible to perform electrochemical reactions on minute traces of  
15 elements in solutions such as contaminants in water, and additionally makes it possible for the mass transfer of electrons in chemical reactions allowing for the high throughput of solutions in industrial applications such as the production of chlorine from salt water.

          In one embodiment of the present invention, a flow-through electrolytic cell is provided using the flow-through electrodes. A number of methods of feeding solutions or gases into the  
20 flow-through electrolytic cell are introduced depending upon the direction of solution flow through the electrodes. Solutions or gases can be either first oxidized in one electrode or reduced or the solution can be fed between the electrodes so that one portion flows through the oxidizing

electrode while the other portion flows through the reducing electrode. This methodology allows the elimination of diaphragms in some electrolytic cells.

Specifically, one aspect of the present invention is an electrochemical cell, comprising:

at least a first and a second three-dimensional flow-through electrode wherein said first  
5 three-dimensional flow-through electrode is a positive electrode and said second three-dimensional flow-through electrode is a negative electrode;

a current feeder associated with each of said three-dimensional flow-through electrodes, wherein at least a substantial portion of each of said current feeders is located within said three-dimensional flow-through electrode associated with said current feeder;

10 a power supply coupled to each of said current feeders to create an electrical potential therebetween; and

wherein the electrochemical cell is operable to facilitate a chemical reaction on a feed solution which is flowing through said electrodes.

Numerous electrochemical processes using these feeding methods are disclosed. These  
15 processes include water treatment, including the purification of contaminated water or the removal of chlorine from drinking water. The processes further include a wide variety of chemical processing, hydro-metallurgical applications, and environmental clean-up, such as remediation of contaminated soil. Further, a method to replace the use of cyanide in gold and silver processing operations is disclosed as well as a method to replace heap-leaching technology  
20 in general using a counter-current, continuous-flow apparatus for ores. Thus, as appreciated by one skilled in the art, the present invention has a multitude of possible applications in numerous industrial and commercial applications.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIGURE 1 is a front perspective view of a basic flow-through electrode in one embodiment of the present invention;

5        FIGURE 2 is a front perspective view of a large flow-through electrode in one embodiment of the present invention;

FIGURE 3 is a front perspective view of a flow-through electrode in another embodiment of the present invention;

10       FIGURE 4 is a cross-sectional view of a flow-through electrolytic cell according to one embodiment of the present invention;

FIGURE 5 is a cross-sectional view of a flow-through electrolytic cell according to another embodiment of the present invention;

FIGURE 6 is a cross-sectional view of a flow-through electrolytic cell according to another embodiment of the present invention;

15       FIGURE 7 is a cross-sectional view of a flow-through electrolytic cell according to another embodiment of the present invention;

FIGURE 8 is a cross-sectional view of a flow-through electrolytic cell according to another embodiment of the present invention;

20       FIGURE 9 is a flow chart diagram illustrating the operational steps for one embodiment of the present invention;

FIGURE 10 is a flow chart diagram illustrating the operational steps of another embodiment of the present invention;

FIGURE 11 is a flow chart diagram illustrating the operational steps of another embodiment of the present invention;

FIGURE 12 is a front elevation view of a mineral processing apparatus of another embodiment of the present invention;

5        FIGURE 13 is a front sectional schematic diagram showing the layout of a series of E-VATs arranged in a train-like setting;

FIGURE 14 is a plan view schematic which illustrates a preferred embodiment of this invention for processing ores and particularly ores containing gold;

10        FIGURE 15 depicts a flow chart showing another embodiment of this invention; a method of recovering metal, in particular, gold, from ores requiring finer particle size preparation for liberation of their mineral values;

FIGURE 16 is a cross section of a typical in situ leaching method for production of uranium from subterranean deposits using another embodiment of this invention for regenerating oxidizing lixivants in a cost effective manner; and

15        FIGURE 17 is a cross section illustration of in irrigation treatment system of one embodiment of the present invention.

## DETAILED DESCRIPTION OF THE DRAWINGS

Referring now to the drawings, FIGURE 1 illustrates one embodiment of the present invention having a flow-through electrode **1** into which a current feeder **2** is inserted. The flow-through electrode **1** can be any conducting material that is porous to the flow of liquids or gases, and, in one embodiment, is graphite felt such as that manufactured by National Specialty Products of Fostoria, Ohio. The current feeder **2** can be any conductor material capable of conducting an electrical current, and, in one embodiment, is a graphite rod having a diameter of about one-quarter inch or larger, and being capable of conducting a current in the range of about 0.01 to 5.0 amperes. Other current feeders may include, for example, copper, steel, or a noble metal such as platinum, palladium, gold, as well as alloys of metals such as tantalum, tungsten, and titanium. The current feeder may also separate base material which is plated with any of the previously mentioned materials. The current feeder **2** is inserted into the flow-through electrode **1** by boring a hole of lesser diameter than the current feeder **2** in the flow-through electrode **1** such that when the current feeder **2** is inserted, the fibers of the graphite felt are in intimate contact with the current feeder **2**, forming a good electrical connection. A current feeder, as referred to herein, is a device which facilitates the supply of electrical current to, or the conduction of electrical current from, an associated electrode. A number of other porous conducting materials could be used for the electrode material such as, for example, steel wool, copper wool, or wool composed of the noble metals such as platinum, palladium or gold, as well as exotic alloys of metals such as tantalum, tungsten and titanium. Graphite felt is utilized in one embodiment for this invention because of its low cost when compared to most alternatives, chemical resistance and its high hydrogen overvoltage potential property.

FIGURE 2 is a front perspective view of a flow-through electrode **100** in one embodiment of the present invention which includes a plurality of current feeders **2**. An electrode of this design containing one cubic foot of graphite felt would have a surface area for electrochemical reactions of about 17,000 square feet. This large surface area allows for relatively efficient reactions to take place. These types of electrochemical reactions are especially useful in numerous applications for removing trace elements from solutions or gases, or the reduction and recovery of valuable metals such as gold, silver, platinum and palladium. In one embodiment, the flow-through electrode **150** is used to produce electrodes for industrial applications requiring large current flows. The flow-through electrode **100**, in another embodiment is used for a fuel cell electrode where the graphite felt is first coated with a suitable catalyst. In such an application the current feeders **2** are also used to remove electricity generated within the electrode. The number and spacing of the current feeders **2** is dependent upon the application and the amount of current required for the application. For example, current of up to at least 50 amperes per square foot (600 amperes per cubic foot) is preferred for chlorine production, while current of about 100 milliamps per square foot is preferred for removal of trace elements from water. The number, size, and spacing of the current feeders vary as necessary for the desired current density. In one embodiment, the current feeders **2**, are covered by a polypropylene geotextile having precut holes. This embodiment is useful when the current feeders **2**, have a relatively high voltage applied to them, which may act to pull the carbon felt apart and cause a cell containing the electrode to short-circuit.

FIGURE 3 is a perspective view of an alternative method of achieving electrical flow into a flow-through electrode **1** where a conductive bar **104** is placed in intimate contact with up



to four sides of the flow-through electrode **1**. This bar **104** can be any conductive material, and in one embodiment is a graphite bar and the flow-through electrode is graphite felt, similar to the flow-through electrode depicted in FIGURE 1. A drawback of this method of feeding electrical current into flow-through electrode **1** is that as the dimensions of the flow-through electrode increases, the resistance to electric current flow also increases due to the resistance of the carbon felt. Accordingly, this design is most advantageous in applications requiring relatively small current flows in the range of about 5 milliamps per square foot up to one ampere per square foot.

FIGURE 4 is a cross-sectional front elevation view of a flow-through electrolytic cell **108** using the basic electrode described in FIGURE 1, where two such flow-through electrodes **1** and **1a**, with current feeders **2** and **2a**, are placed in a container **3** made from inert material, such as a variety of plastics including PVC, HDPE, Acrylic, or any other suitable material that is not a conductor of electricity and is not chemically reactive with any of the gases or liquids used in the electrolytic cell **108**. Such containers may be either open-top or totally enclosed, depending on the application. The flow-through electrodes **1** and **1a** separate the electrolytic cell **108** into three specific chambers **4**, **5**, **6**. As appreciated by one skilled in the art, any possible number of geometric configurations may be utilized depending on the application, and including other chambers when a plurality of electrodes are put into series and also using combinations of cells including series, parallel, and cascade configurations. In this embodiment, a solution, or gas, enters the flow-through electrolytic cell **108** from stream **7** (under sufficient hydraulic pressure to induce flow) through a valve (not shown) into chamber **4** where it passes through a negatively-charged electrode **1a** into chamber **5** and then through a positively-charged electrode **1** and into chamber **6** where the product stream **8** exits through an exit valve (not shown). Both the current

feeders **2, 2a** are connected to a direct current power supply (not shown). In this unit a direct electrical current is applied through current feeder **2** into positive electrode **1** and negative electrode **1a** and into current feeder **2a** to complete the circuit. The amount of current and voltage is dependent upon solution composition and desired results.

5           One application for a flow-through electrode **108** of this embodiment includes stream **7** which is composed of a solution of water and sodium chloride. In the negative electrode **1a**, under sufficient voltage of at least about 3 volts, and, more preferably about 5-10 volts, some of the water is electrolytically separated into hydrogen gas and hydroxide ions. The hydrogen gas is vented from chambers **4** and **5** (not shown), while the solution, with its increased hydroxide ion  
10   level passes into chamber **5** and then through the positive flow-through electrode **1** where some of the chloride ions are oxidized to free chlorine which immediately reacts with the hydroxide to form a hypochlorite ion within the flow-through electrode **1** and within chamber **6** so that the product leaving the flow-through electrolytic cell is a solution of water, sodium chloride and sodium hypochlorite (a common chemical used as household bleach, swimming pool disinfectant  
15   and numerous industrial processes).

FIGURE 5 is similar to FIGURE 4 as to the design and construction of the flow-through electrolytic cell. The primary distinction is in the direction of flow of solutions or gases to be processed. In this embodiment, solutions or gases to be processed in the flow stream **9** are introduced into chamber **5** through a valve (not shown) where a portion of the solution passes  
20   through a negative electrode **1a** and the remainder of the solution passes through the positive electrode **1**. In this unit a direct electrical current is applied through current feeders **2, 2a** into positive electrode **1** and negative electrode **1a**, the amount of current and voltage is dependant

upon solution composition and desired results. Thus through an electrolytic process, stream 9 is separated into two different products, including stream 7 and stream 8.

As an example of this embodiment, a solution of sodium chloride and water is fed into chamber 5 as stream 9. A portion of the solution passes through the negative flow-through electrode 1a into chamber 4 and the remaining portion of solution passes through the positive electrode 1 into chamber 6. The amount of each product stream 7 and 8 is regulated by a valve (not shown) on chambers 4 and 6. In the negative electrode 1a water is electrolytically separated into hydrogen gas and into hydroxide ions while in the positive flow-through electrode 1 the chloride ion is oxidized to chlorine gas which dissolves into water to form hypochlorous acid. Thus the solution in chamber 4 is enriched in sodium hydroxide while the solution in chamber 6 is enriched in hypochlorous acid. The pH of the solution in chamber 4 is substantially basic while that of the solution in chamber 6 is substantially acidic. The inventor has conducted tests where the pH in chamber 4 reached in excess of pH 13, while the pH of chamber 6 was as low as 1. These results can be varied by controlling the voltage to the electrodes, the solution flow rate through each electrode and the composition of the original solution. For example, in one test, a voltage of 9 volts, with a starting solution of 2 percent sodium chloride was used, resulting in a flow rate of 70 ml/min for each electrode, and each electrode was 4 inches by 4 inches by 1 inch thick. The resulting solution in chamber 6 had a pH of 3.8 and an ORP of 1,045 millivolts, and a solution in chamber 4 had a pH of 11.7 with an ORP of 37 millivolts.

It will be obvious to one skilled in the art that this is a fundamental electrochemical cell with the ability to separate any salts into their original acidic and basic components. It will also be obvious to one skilled in the art that this embodiment allows electrochemical processes to be

conducted without the use of a diaphragm to separate anode and cathode products. The flow-through nature of the electrodes **1a** and **1** used within substantially prevents the back-flow of products due to the fact that electrical charge on the flow-through electrodes **1a** and **1** repels ions or products with the same charge. For example, the hydroxide ion produced in the negative  
5 electrode **1a** will not flow from chamber **4** into chamber **5** because it would have to traverse the thickness of the negative electrode **1a** that has a repelling charge.

FIGURE 6 is similar to FIGURE 4 in the construction of the flow-through electrolytic cell. The primary distinction is that the solutions or gases to be processed, as depicted as stream **11**, first enter chamber **6** where they first flow through the positive electrode **1**, then into chamber  
10 **5** where they flow through the negative electrode **1a** into chamber **4** and exit as product stream **10**. In this specific embodiment, a direct electrical current is applied through current feeders **2**, **2a** into positive electrode **1** and negative electrode **1a**, the amount of current and voltage is dependant upon solution composition and desired results.

One specific application of this embodiment is in the treatment of contaminated water to  
15 provide water suitable for human consumption. Untreated water, with sediments removed, is processed as depicted in stream **11** where it enters chamber **6** and passes through the positively charged flow-through electrode **1**. Within this electrode, some existing chloride ions (which are common to all natural water) are oxidized to chlorine and micro-organisms are subjected to an electric current. Both the electric current and the chlorine act to kill substantially all of the  
20 disease-causing micro-organisms. Trace organic harmful compounds are oxidized as well. The oxidized solution flows into chamber **5** and then through the negative electrode **1a** where the chlorine produced within the positive electrode is reduced back to chloride and transition metals

present in the original untreated water are electro-deposited within the negative flow-through electrode **1a**. The resulting solution in chamber **4** and exiting as stream **10** is potable water. The current and voltages necessary for this embodiment can readily be produced by an inexpensive solar cell, which produces at least about 1.7 amp, 9 volts, and 15 watts. Most any other means of electricity generation, such as wind power or a small hydroelectric generator could also readily produce the current and voltages necessary for this embodiment. Voltage is the most important factor and is preferably at least about 3 volts. It is contemplated that this embodiment may have widespread usage worldwide to provide potable water in remote locations not in proximity to a power grid.

FIGURE 7 is similar to FIGURE 6 with the addition of the option of removing a stream **12** from the inter-electrode chamber **5** through a valve (not shown). This embodiment allows the removal of an additional product. For example, using the water purification example of FIGURE 5, a stream **12** could be removed from chamber **5** that has a high Oxidation-Reduction Potential (ORP) due to the chlorine produced within the positive electrode. Such a stream is useful in cleaning households and household items. In testing, this stream has had a measured ORP of between +600 millivolts to +1100 millivolts. Thus, this embodiment allows the treatment of raw water to produce both drinkable water and a solution useful in cleaning unsanitary conditions, utensils, or any other items.

FIGURE 8 is similar to FIGURE 4 with the addition of stream **12** removed from the inter-electrode chamber **5** through a valve (not shown). This embodiment allows the production of two products from a process stream **10**. One example of this embodiment would be the processing of a solution of water and sodium chloride entering chamber **4** as process stream **10**,

where it first passes through the negative flow-through electrode **1a**. In one embodiment, a direct electrical current is applied through current feeders **2, 2a** into positive electrode **1** and negative electrode **1a**, the amount of current and voltage is dependant upon solution composition and desired results. More specifically, this application may be used to produce sodium hypochlorite from low concentration salt solutions. An optional circulating loop **13** of solution raises the pH of the product in chamber **5** to the point where it will dissolve all of the chlorine produced in electrode **1**. The production of chlorine from low salt solutions is generally hampered by the competing production of oxygen at the electrode. As will be understood, this embodiment may have important usage in other electrochemical processes.

In electrode **1a**, water is electrolytically separated into hydrogen gas and hydroxide ions. The hydrogen gas may be removed from chambers **4** and **5** through valves (not shown) while the hydroxide ion enriched solution passes into chamber **5** where a portion of it may be withdrawn through process stream **12** for further usage, including recycling it back to process stream **10** by process stream **13** in order to increase the strength of the incoming solution **10** in hydroxide ions.

In this embodiment, the concentration of hydroxide ions in input stream **10** can be increased by the recycling the solution from chamber **5**. The solution moving through the positive flow-through electrode **1** is thus more concentrated in hydroxide ions. The chlorine produced in the positive flow-through electrode **1** reacts with the hydroxide ions to form hypochlorite with the resulting solution in chamber **6** and represented by product stream **11**, which in this example is a solution of sodium hypochlorite, a commonly used industrial compound. Thus, in this embodiment, a solution process stream **10** of water and sodium chloride can be separated into three products, hydrogen gas, sodium hydroxide and sodium hypochlorite.

FIGURE 9 illustrates another embodiment of the present invention. It is a generalized flow diagram of a process to treat industrial waste water containing cyanide and metals in solution. One such source of this type of metal laden solution is, for example, from electroplating operations.

Another source is from mining operations, such as gold and silver heap leaching operations such as

the one at the Florida Canyon Mine located in Humboldt County, Nevada. In this embodiment, a

source solution **20** containing a cyanide and dissolved metals is pumped into a closed mixing tank

**22** through process line **24**. In the mixing tank **22** an oxidizing solution containing chlorine and

oxygen from process line **8** is mixed with the source solution **20**. In this mixing tank **22**, the

chlorine and oxygen destroy the cyanide by oxidizing it to nitrogen and carbon dioxide. Also

oxidized are metals in a reduced state such as ferrous iron and arsenic compounds. This oxidized

solution leaves the mixing tank **22** through process line **10** where it enters the inner-electrode

chamber **5** of the flow-through electrolytic cell **3**. In this unit, a direct electrical current is applied

through current feeders **2, 2a** into positive electrode **1** and negative electrode **1a**. The natural

amount of current and voltage applied to electrodes **1, 1a** is dependant upon solution composition

and desired results. More specifically, the voltage must be high enough to produce either chlorine

or oxygen or both, and in one embodiment is above about 3 volts. The current is dependent upon

the concentration of the dissolved salts, a salt solution of 500 ppm or more would draw a much

larger current than a solution with only 50 ppm dissolved salts.

A portion of the solution passes through the positive charged three-dimensional

flow-through electrode **1**, in which chloride ions present in the original solution are oxidized to

chlorine and some water molecules are oxidized to produce oxygen. This oxidizing solution passes

from the flow-through electrode **1** into chamber **4** of the flow-through electrolytic cell **3** and then

into process line 8 through a regulating valve (not shown). The remaining solution in chamber 5 passes through flow-through electrode 1a which, in this embodiment, is made of a wire mesh of a conducting material such as copper, lead, or stainless steel. This electrode 1a has sufficient openings to allow passage of precipitated metals and metal compounds. The electro-chemical reactions occurring in and around this electrode are of a reducing nature such that some metals are electro-deposited on the wire mesh while water is reduced to produce hydrogen and hydroxide ions. Some metals precipitate as hydroxides, others as oxides and some are further reduced by the action of the dissolved and entrained hydrogen in chamber 6. As will be understood by one trained in the art, the electro-chemical reactions in, at, and around electrode 1a will depend upon metal concentration, applied voltage, current flow, solution flow rate and solution composition. Indeed, when using a solution with 5000 parts per million sodium chloride and when this electrode is operated at a voltage in the range of 4 to 9 volts and a current density of 50 amperes per square foot, the solution passing through this electrode 1a virtually boils with hydrogen gas bubbles and has an Oxidation-Reduction Potential of minus 1000 millivolts or lower. This reduced solution leaves chamber 6 through process line 7 and may be stored in a treated solution tank 26.

Another embodiment of the present invention is used in an agricultural setting. In this embodiment, water used for irrigation of plants is generated by an electrolytic cell of the present invention. The electrolytic cell includes a negatively charged electrode of copper wire screen and a positively charged electrode of graphite felt. The copper wire screen electrode of this embodiment allows irrigation water to pass through without removing substantial amounts of transported nutrients. Standard irrigation water is fed into the inter-electrode spacing and most of it, approximately ninety percent in one embodiment, is allowed to pass through the negatively charged



copper wire screen electrode and collected in an inert tank. The water passing through the positively-charged electrode is discarded in one embodiment. The cell of this embodiment is operated at a direct current of about 9 volts and approximately 3 to 5 amperes of current. Each electrode was 12 inches square and one inch thick. The water produced through the negative electrode has an oxidation-reduction potential of approximately -300 to -600 millivolts. This is by definition, an anti-oxidant water, as it donates electrons to reduce oxidants and free-radicals. This water is then taken from the inert tank and used as irrigation water.

In one example of the irrigation embodiment, a test garden was planted by the inventor. The garden was divided into two substantially identical sides. One side was irrigated with water directly from a pond while the other side was irrigated with pond water that had passed through the above-described electrolytic cell. Two tanks of 300 gallons capacity were filled for each irrigation event, normally three days apart. One tank was filled with the raw pond water, while the other tank was filled with hydrogen-rich water generated by the flow-through electrolytic cell.

A variety of vegetables were planted and notes were taken on a daily basis. It was observed that the vegetables irrigated with the hydrogen-rich water germinated faster and grew slightly faster compared to the vegetables irrigated with untreated water. In general, the portion irrigated with the hydrogen-rich water looked healthier. No insecticides or fertilizers were used. Later in the summer, problems were encountered with the irrigation lines plugging with algae from the pond water. This led to a less than ideal watering situation. It was noted that the side irrigated with the hydrogen-rich water exhibited little sign of wilting when without water for several days while the other side of the garden showed moderate to severe heat stress when without water for several days. In the fall, a test plot of carrots from each side of the garden was dug. All of the carrots in each plot were extracted,

cleaned, had their tops cut off, and weighed. It was observed that the average carrot irrigated with hydrogen-rich water was 49 percent heavier and larger than those that were irrigated with the raw pond water.

Another example involves numerous other flow-through electrolytic cells which have been constructed and tested using tap water as a source using the scheme depicted in FIGURE 5. The tap water was fed into the inter-electrode space and allowed to flow through each side of the electrolytic cell without restriction. Approximately forty percent of the water passed through the negatively-charged electrode while approximately sixty percent of the water passed through the positively-charged electrode. The electrodes were connected to a direct current power supply with a 9 volt potential. The cells drew an average of 1 ampere per square foot of electrode. When the feed tap water had an ORP of about +450 millivolts due to dissolved chlorine, the water that passed through the negative electrode had an ORP of about -100 millivolts while the water that passed through the positive electrode had an ORP of about +550 to +600 millivolts. Tiny bubbles of hydrogen could be observed in the water that passed through the negative electrode.

In one test, an equal volume of this hydrogen-rich water was mixed with an equal volume of tap water and an ORP calomel reference probe was inserted. The ORP of the mixture dropped from the about +450 millivolts of the tap water to about +100 millivolts of the mixture within about two minutes. This is a demonstration of the anti-oxidant nature of the hydrogen-rich water. The hydrogen-rich water had the effect of neutralizing the chlorine (a free radical oxidant) in the water mixture. Furthermore, a taste test demonstrated no chlorine taste.

FIGURE 10 illustrates another embodiment of the present invention. In this embodiment, the solution source 30 is a liquid containing dissolved metals including, but not limited to, gold,

silver, copper, lead and zinc, but does not contain cyanide. Such a solution could originate from many industrial processes, such as, for example, metal plating, ore processing or scrap recycling, and would most likely be acidic. The solution could also be from polluted sources such as acid mine drainage. This solution may contain chlorides, nitrates, sulfates or phosphates. In this embodiment, solution **30** flows through process line **34** to mixing tank **32** where it is mixed with a reducing alkaline solution from chamber **6** in the flow-through electrolytic cell **3** which flows through process line **7** to the mixing tank **32**. In the mixing tank **32** two types of reactions occur, wherein one is a reducing reaction of the metals to metal powder by the action of hydrogen produced within the electrode **1a** by the electrolytic reduction of water. This also produces an increase in the hydroxide ion content of the solutions which may cause a second reaction to simultaneously occur including the precipitation of metal hydroxides. As will be understood by one skilled in the art, the chemical reactions may potentially remove virtually all metals in the solution due to the low solubility of metal hydroxides in reducing alkaline water. One skilled in the art will also recognize that the chemical processes occurring in mixing tank **32** can be drawn out into individual reactions in separate mixing tanks by first separating the hydrogen gas in process stream **7** from the hydroxide rich liquid so that the original solution can have its pH raised in increments by addition of hydroxide rich liquid separated from process stream **7** to allow individual metal hydroxides to precipitate. The Oxidation-Reduction Potential of the process stream **34** could also be regulated with the addition of controlled amounts of the separated hydrogen gas, thus sequentially reducing dissolved metals according to their respective oxidation-reduction potentials.

The reduced alkaline solution from mixing tank **32** flows through process line **34** into filter **36** where solids **38** containing metal powders, metal oxide powders and/or metal hydroxides are

removed for environmentally safe disposal or metal recovery. The resulting metal-free liquid from the filter 36 flows through process line 10 into chamber 5 of flow-through electrolytic cell 3. In this unit a direct electrical current is applied through current feeders 2, 2a into positive electrode 1 and negative electrode 1a. The amount of current and voltage is dependant upon solution composition and desired results. Part of the solution flows through negative electrode 1a where hydrogen gas and hydroxide ions are produced for the recycled solution in process line 7, while the remainder of the solution in chamber 5 flows through positive electrode 1 where the hydroxide ions are neutralized by the electrolytic oxidation of water which can reduce the pH level to 7 which is neutral. Thus the solutions leaving chamber 4 through process stream 8 is a substantially metal-free, clean solution which may be stored in treated solution tank 40.

FIGURE 11 illustrates another embodiment of this invention which generally depicts a process diagram for recovering metals from ores, including, but not limited to gold, silver, copper, lead, zinc, tin, cobalt, platinum and palladium. In this embodiment, crushed ore 50 is conveyed by conveyor 54 into device 56, herein called the E-VAT, which is a continuous flow, counter-current leaching system. Lixivating solution 8 such as a solution of 1/10% to 30% sodium chloride and 0% to 15% sodium bromide, is added to the ore in the E-VAT 56 after first passing through the electrode 1 where it is oxidized to produce sufficient chlorine, bromine or compounds of both so that it dissolves the targeted metal contained within the ore resulting in a pregnant solution which leaves the E-VAT 56 through process line 58. At the same time, leached ore is transported through rinsing mechanism 60 where fresh water from process line 62 is added to displace entrained liquids in the leached ore so that a rinsed and leached ore 64 is produced for further environmentally safe disposal. The fresh water 62 is derived from a portion of lixiviant solution in process line 8 through

a salt/water separator **66** using reverse osmosis, electro-dialysis or another effective method to produce fresh water from salt water. The waste solution **68** from the salt/water separator **66** is added back to the lixiviant solution in line **8** through process line **70**. The pregnant solution containing the targeted metals flows through process line **58** into mixing tank **72**, where a solution coming from chamber **6** of flow-through electrolytic cell **3** is added through process line **7**. In this mixing tank **72**, at least two chemical reactions occur, the first being the reduction of metals by hydrogen gas entrained in the solution from process line **7**, and the second reaction being the precipitation of metal hydroxides and oxides by the hydroxide ions in the solution from process line **7**. It will be understood by one skilled in the art as to which type of these reactions occur depends upon the metals present, their concentration, the pH and Eh of the pregnant solution.

The precipitated solution leaves mixing tank **72** through process line **74** where it passes into filter **76** where the precipitated metals and metal compounds are removed as filter cake **78** which can be mixed with fluxes such as borax, sodium carbonate, fluorite, silica, and lime, and melted to produce metal bullion, if desired. The barren solution filtrate from the filter **76** leaves through process line **10** where it enters chamber **5**, the inter-electrode chamber, of flow-through electrolytic cell **3**. In this unit a direct electrical current is applied through current feeders **2**, **2a** into positive electrode **1** and negative electrode **1a**, the amount of current and voltage is dependant upon solution composition and desired results. In one embodiment, the flow rate through process line **10** is about 100 mL/min and the flow-through electrodes **1**, **1a** are each about 4 inches per side and one inch thick. It will be understood that flow rates may vary based on the size of the electrodes, the current and voltage, and the solution being fed into the electrolytic cell.

A portion of the barren solution passes through flow-through electrode **1a** where water is separated into hydrogen gas and hydroxide ions and enters chamber **6** where it is recycled to mixing tank **72** for metal precipitation. The remaining barren solution passes through flow-through electrode **1** where it is oxidized by the electrolytic process so that any chloride or bromide ions are oxidized to chlorine and bromine and their compounds which dissolve in the solution in chamber **4** to form hypochlorous acid or hydrobromous acid, dependant upon solution chemistry. The pH of this solution may also be lowered by the oxidation of water to produce oxygen and hydrogen ions. This solution is now the lixiviant which flows through process line **8** back to the E-VAT leaching system. Thus, this embodiment of the invention is a closed system to recover metals from their ores, waste materials or scrap using the flow-through electrodes **1** in a flow-through electrolytic cell.

An example of the embodiment is now described. Gold ores have been tested using a system of this embodiment, resulting in a recovery of contained gold which was over eighty-two percent in an ore containing 5 grams of gold per ton, in four hours of leaching time. This is approximately twenty times faster than conventional leaching techniques which require leaching the gold with cyanide. The lixiviant used in one embodiment is a solution of water and sodium chloride, with and without sodium bromide. Thus, this embodiment can replace the usage of cyanide for such leaching applications which is currently used world-wide, with occasional horrific environmental consequences. Table 1 contains results from one test of a system of this embodiment.

**TABLE 1**

**STEALTH LEACH TEST**

Sample Designation	Gold								
	PPM	Soln Wt. gms	Ore Wt. 200	Ratio	Gold Rec ppm	%Rec	Cum Rec	Time minutes	Hours
ST-1	1.02	85	200	0.425	0.43	7.55%	7.55%	25	0.42
ST-2	1.56	145	200	0.725	1.13	19.71%	27.27%	85	1.42
ST-3	1.23	2.89	200	1.445	1.78	30.98%	58.24%	145	2.42
ST-4	0.93	304	200	1.52	1.41	24.64%	82.88%	205	3.42
ST-5	0.14	4.36	200	2.18	0.34	5.32%	88.20%	445	7.42
ST-6	0.05	5.0	200	2.65	0.13	2.31%	90.50%	1440	24.00
					5.19	90.50%			
					0.151	Oz/tn	90.50% recovered		
					0.548	0.016	Tails assay	9.50% tails	
					5.738	0.167	head grade	100.00%	

FIGURE 12 is a sectional, front elevation view of one embodiment of the continuous-flow counter-current leaching system, referred to as the E-VAT, of FIGURE 11. In this system, two round cone-bottomed tanks **150** and **154**, made from rotary molded hi-density polyethylene or other suitable material are positioned vertically above each other and supported by a structural steel silo **158**. The tanks are connected by a feed tube **162** through which crushed ore **166** stored in tank **150**, used as an ore bin passes into tank **154**, used as a leaching reactor, where the ore is contacted with a lixiviant solution which enters through pipe **170**. The lixiviant solution **172** flows up through the crushed ore in tank **154** where it dissolves the desired elements and becomes pregnant solution **174**, which exits through pipe **178** (equivalent to process line 11 of FIGURE 11). The crushed ore flows

down through tank **154** (the leaching reactor) by gravity where it flows through outlet pipe **182** into  
auger **186**. It moves up auger **186**, powered by variable speed motor drive mechanism **190**. Fresh  
water is injected into the auger through pipe **194** where it displaces entrained solutions. The fresh  
water is injected at a point above the liquid level **198** in tank **154** (the leaching reactor) so that the  
5 fresh water flows down the auger by gravity. The leached and rinsed ore then exits the auger **186**  
through discharge pipe **202** where it falls to the ground as pile **206** for further environmentally safe  
disposal. The auger **186** is fitted with a clean-out plug **210** and drain pipe **214**.

In this system, the crushed ore flows by gravity down through the leaching reactor **154** while  
the lixiviant flows up through the ore. The strongest solution therefore contacts the weakest (lowest  
10 metal content) ore which is the ideal metallurgical condition to maximize metal recovery and  
minimize reagent consumption. The flow rate of ore through the E-VAT is easily regulated by  
adjusting the speed of the auger through the variable speed motor drive mechanism **190**. The  
solution flow rate, and thus the residence time, in the leaching reactor is readily regulated by the  
injection rate of the solution.

15 FIGURE 13 is a front sectional schematic diagram showing the layout of a series of E-VATs  
arranged in a train-like setting. Only major components are depicted. In this embodiment, crushed  
ore is fed into ore hopper **301** where it is conveyed via auger **302** into ore hopper **303**. The ore  
flows by gravity down through E-VAT unit **304**, is conveyed via auger **305** into E-VAT unit **306**,  
where it flows by gravity into auger **307** which conveys it into E-VAT unit **308** where it flows by  
20 gravity into auger **309** which conveys it into E-VAT unit **310** where it flows by gravity into auger  
**311** which conveys it into E-VAT unit **312** where it flows by gravity into auger **313** where it is  
conveyed for disposal. In this embodiment, the ore can flow either continuously, or in batches,



depending upon the processing needs. Lixivants are injected into the bottom of each E-VAT unit and removed from the upper portion of the same unit as depicted more fully in FIGURE 12.

FIGURE 14 is a plan view schematic which illustrates an embodiment of this invention for processing ores and particularly ores containing gold. In this embodiment, crushed ore is placed

5 into ore hopper **401**. The fineness of crushing is dependent upon the particular leaching requirements of the ore. The ore enters an auger **403** where it is conveyed into E-VAT unit **404**. At a point shortly after entering the auger **403**, an agglomerating agent such as Portland cement, long-chained polymers, flocculates or other suitable binding agent is added from tank **402**. The addition of the agglomerating agent coupled with the rotary action of the auger **403** while conveying the ore  
10 has the effect of agglomerating the ore by attaching fine particles to larger ones. The auger **403** can also be discharged into an ore bin vertically above E-VAT **404** as depicted by **303** in FIGURE 13.

This ore bin can be sized to allow curing time for the agglomerating agent, or if necessary, an additional E-VAT unit without any liquid additions can be used at this point in the process for longer curing times. In E-VAT unit **404** a lixivating agent is injected into the bottom of the unit

15 where it percolates up through the crushed and agglomerated ore reacting with, and dissolving metals. This metal-laden pregnant solution flows from the upper portion of the E-VAT unit **404** into pregnant storage tank **414**. The pregnant solution is then pumped through flow-through electrolytic cell **419** as depicted in FIGURE 4. The contained metals of the pregnant solution are deposited in the negatively-charged flow-through electrode. The lixiviant is restored when it passes  
20 through the positively-charged flow-through electrode. The restored and regenerated lixiviant flows into storage tank **423** from which it is then pumped back into E-VAT unit **404**, this forming a completed closed circuit of solution flow.

From E-VAT unit **404** the partially leached ore passes into transfer auger **405** where it is conveyed into E-VAT unit **406** where the leaching cycle is repeated as described above for E-VAT unit **404**. These steps are repeated in E-VAT units **408**, **410** and finally in **412** at which point substantially all of the metal is leached out. As will be understood, additional E-VATs may be added in series, or in parallel, to the apparatus illustrated in FIGURE 14. A rinsing solution of clean water can be added at the end of auger **413** as shown in **194** of FIGURE 12.

The need for multiple E-VAT units in series should be obvious to one skilled in the field. Fresh ore entering the top of E-VAT unit **404** may be reactive enough to precipitate dissolved metal thus preventing the metal from leaving the vessel. This could possibly happen if the ore contained sulfides and the dissolved metal was gold. Another function of the series arrangement is to prevent ore particles from short-circuiting the E-VAT unit and not receiving the full leaching time necessary to dissolve all of the metal contained in the particle.

Still another advantage of the series arrangement of multiple E-VAT units and associated electrolytic cells, pumps and tanks is the ability to selectively leach and remove intended minerals or metals. In one example utilizing an apparatus illustrated in FIGURE 14, the Inventor operated the apparatus for leaching an ore containing polymetallic sulfides, with solutions containing both sodium chloride and sodium bromide which, when passed through a positively-charged flow-through electrode, were partially converted in chlorine and bromine and their compounds. It was observed that the metals in the sulfides were leached in the following order. First, the lead sulfides dissolved, followed by the zinc sulfides and then the copper sulfides dissolved. This was followed by dissolution of gold while the contained silver remained in the ore as silver chloride and silver bromide.

Using a system such as illustrated in FIGURE 14, a polymetallic ore containing metal sulfides can be treated in sequence. First the lead is leached in E-VAT unit **404** and recovered in flow-through electrolytic cell **419**, then the zinc is leached in E-VAT unit **406** and recovered in flow-through electrolytic cell **420**. Next the copper is leached in E-VAT unit **408** and recovered in flow-through electrolytic cell **421**. Gold is then leached in E-VAT unit **410** and recovered in flow-through electrolytic cell **422**. Finally, silver is leached in E-VAT unit **412** and recovered in flow-through electrolytic cell **423**.

It should be obvious to one skilled in the art, that the lixivants used in a multiple stage process can be diverse. For example, to recover lead and zinc from polymetallic sulfide ores, a starting solution containing only sodium chloride could be used while the addition of sodium bromide may increase the recovery of copper in the next stage and increases the recovery of gold in the gold stage. Silver requires the use of a different lixiviant than used in the previous stages as the silver halides are insoluble in water, but the silver can be recovered in this stage by the use of solutions containing thiosulfate, ammonia, salt brine, or a number of organic compounds.

It will be understood by one skilled in the art that the solutions could also flow through multiple units in a counter-current direction with or without passing through an electrolytic cell. Such a flow scheme may be of use to increase the metal content of the pregnant solution prior to stripping in an electrolytic cell. It also should be understood by one skilled in the art, that other methods of removing metals from pregnant solutions could be used prior to lixiviant regeneration including cementation with another metals, ion exchange, or crystallization of a metal salt such as lead chloride recovered by simply cooling a saturated hot solution.

It should also be understood by one skilled in the art, that this multiple stage process can be used to treat a vast variety of solids whereby the solids are treated by different lixivants for different objectives. The solids could be ores containing metals or scrap materials such as granulated electronic circuit boards. The solids could also be contaminated soils where there is a need to remove environmentally hazardous compounds as simple as salty soil to that containing radioactive compounds. One skilled in the art will also readily recognize that the liquids used need not be confined to water solutions but could as well be any number of organic liquid compounds.

FIGURE 15 illustrates yet another embodiment of the present invention. It depicts a flow chart of the operational steps for a method of recovering metal, in particular, gold, from ores requiring finer particle size preparation for liberation of their mineral values. Crushed ore, prepared by any number of conventional methods, enters ball mill **501** through process stream **500** and discharges through process stream **502** where additional water is added from process stream **509**. The ground ore slurry enters classifier **503** where oversize material is separated and returned to the ball mill **501** through process stream **504** while diluted undersize material flows through process line **505** into thickener **506** where the ore slurry is thickened to a pulp density between 40 to 70 percent, more preferably 60 to 70 percent. The excess water from the thickener is decanted through process line **507** into storage tank **508** while the thickened slurry is pumped (pump not shown) through process line **510** into mixing tank **511** where lixiviant is added. The lixiviant should have a pH between 3 and 8 (dependent upon the chemistry of the ore), a sodium chloride content of between 0.1 and 25 percent, a sodium bromide content between 0.05 and 5 percent and an oxidation-reduction potential (as measured with a calomel-platinum probe) in excess of +650 millivolts, more preferably +850 to +950 millivolts, due to the generation of dissolved chlorine and

bromine and their compounds. This lixiviant is generated in the positively charged flow-through electrode of electrolytic cell **529**. Sufficient lixiviant is added to dilute the pulp density of the incoming ground ore slurry to between 10 and 35 percent solids, more preferably to 25 percent solids. It should be noted that all equipment from the mixing tank **511** to the end of the process should be constructed of non-corroding material, and in an embodiment is constructed of HDPE plastic, and should be totally enclosed to prevent any loss of chlorine or bromine vapors. The ground ore slurry, with the added lixiviant, leaves mixing tank **511** through process line **512** into pump **513** where it is injected into the bottom of reactor **515** through process line **514**, it departs reactor **515** through process line **516** where it enters pump **517** and is injected into the bottom of reactor **519** through process line **518**. It departs through process line **520** into pump **521** where it is injected into the bottom of reactor **523** through process line **522**. In one embodiment mixing tank **511** and reactors **515**, **519**, **523** are cone-bottomed covered vessels of rotary-cast hi-density polyethylene (HDPE). The conical shape of the bottom insures that all of the ore particles are in motion and subject to the action of the lixiviant. It has the added advantage of allowing any occasional coarse gold particles (due to their heavy nature) to remain trapped in the vessel until they dissolve. A minimum of three reactors is utilized in this embodiment to prevent any material from short circuiting the vessel and not getting full time exposure to the lixiviant. The slurry residence time in each reactor **515**, **519**, and **523** is from less than 30 minutes to about 4 hours, preferably about 1 hour, dependant upon the natural chemistry of the ore.

The ore slurry, with dissolved metals, leaves reactor **523** through process line **524** into pump **525** which transfers it to thickener **527** through process line **526**. In thickener **527**, the solids are separated from most of the liquid containing the dissolved metals. This pregnant solution leaves

through process line **528** where it is joined with additional pregnant solution from filter **544** through process line **543**. The combined streams flow into flow-through electrolytic cell **529** where gold and other metals are deposited in and on the negatively charged flow-through electrode, as also depicted in FIGURE 7. The now barren solution flows into the inter-electrode space, where a portion of it flows through process line **546** to evaporator **536** (to maintain salt water balance) while the remainder flows through the positively-charged flow-through electrode where both chloride and bromide are oxidized to chlorine and bromine and their compounds. This is now the lixiviant which leaves the flow-through electrolytic cell **529** through process line **530** where it is stored in lixiviant tank **531** from which it leaves through process line **532** into pump **533** which injects it through process line **534** into the bottom of mixing tank **511**.

The thickened leached ore is pumped from thickener **544** (pump not shown) into filter **544** where additional pregnant solution is removed through process line **543**. Within the filter **544**, the filter cake is rinsed with fresh water (source not shown) to removed any entrained lixiviant. The rinsed filter cake, which is the leached ore residue, is then sent to disposal shown as **545**. This disposal should be upon a liner to prevent any migration of trace amounts of metals into the environment.

The rinse solution from the filter **544** leaves through process line **542** and enters flow-through electrolytic cell **541**. It enters between the positive and negative charged flow-through electrodes as shown in FIGURE 5. Any residual gold and other metal is recovered within the negatively-charged flow-through electrode which also generates an excess of dissolved hydrogen gas. This solution leaves through process line **540**. A portion of the process stream flows through the positively-charged flow-through electrode where some of the residual chloride and bromide is

oxidized to chlorine and bromine and their compounds and leaves through process line 539 where it is mixed with the solution from process line 540 in tank 538 where the dissolved hydrogen reduces the chlorine and bromine contained in process line 539 back to harmless chloride and bromide. The now neutralized dilute saline solution leaves tank 538 through process line 537 into evaporator 536.

5 This could be any commercial evaporator or simply a series of small evaporation ponds. The purpose of this step is to increase the concentration of dissolved salts to match that of the lixiviant. The now concentrated salt solution is fed into lixiviant tank 531 through process line 535. In another embodiment, the amount of solution entering the evaporation step from line 546 can be dramatically reduced by grinding the ore in a spent lixiviant solution rather than fresh water.

10 The E-VAT continuous-flow counter-current leaching system of the present invention has the ability to replace current heap-leaching technology commonly used in the mining industry. In heap-leaching technology, a large pile of ore is placed on an impervious leach pad and sprayed or irrigated with leaching solutions which migrate down through the ore, dissolving metals. In many cases, the heaps continue to have additional ore added to them until they reach enormous size, over  
15 hundreds of millions of tons. These pads are saturated with the leaching solution. In the case of gold and silver ores, the leaching solution contains cyanide. In the case of copper ores, the leaching solution contains sulfuric acid and iron salts. Thus, at the end of their economic life, heap leach pads may contain enormous amounts of toxic materials in the solutions which leads to potentially catastrophic environmental disaster risks. The E-VAT continuous-flow counter-current leaching  
20 system leaches the ore and then rinses the leached ore on a continuous basis so that there is no accumulated environmental risk like there is in a heap leach. Thus the risk to the environment is drastically reduced, if not eliminated.

FIGURE 16 illustrates another embodiment of this invention. The figure is a cross section of a typical in-situ leaching situation for uranium similar to those discussed by Hard et al. in US Patent 3,708,206 and Habib, Jr., et al. in US Patent 4,312,840 and Camp, et al. in U. S Patent 4,476,099. In this diagram, a porous ore horizon **601** containing valuable uranium deposits, is sandwiched between two impermeable beds **602** and **603** which protect underlying rock formation **605** and overlying gravel **604** from contamination by solutions originating in ore horizon **601**. In this case, a lixiviant containing alkali metal bicarbonate, or carbonate and hypochlorite solutions at a pH in excess of 7, more preferably between 8-10 is injected through process line **615** into Injection Well **606** where it enters porous ore horizon **601** wherein the lixiviant dissolves uranium minerals. The metal-laden lixiviant is withdrawn from the porous ore horizon **601** by Recovery Wells 1 and 2, **607** and **608**, where it flows through process line **607** into pregnant solution tank **608** and then through process line **609** into precipitation apparatus **610** where the pH of the pregnant solution is lowered and sufficient phosphate is added to precipitate the contained uranium values as discussed, for example, by Camp, et al. in U. S Patent 4,476,099. The mechanism of recovering the precipitate is not shown in this diagram. The now barren solution leaves the precipitation apparatus **610** through process line **611** where it enters flow-through electrolytic cell **612**. The details of this particular embodiment of the flow-through cell 612 are depicted in FIGURE 4. The pH of the lixiviant is increased and restored to the range of 8-10 within the negatively charged flow-through electrode by the electrolytic reduction of the water according to the equation  $2\text{H}_2\text{O} + 2\text{e}^- \rightarrow \text{H}_2 + 2\text{OH}^-$ , the lixiviant then flows through the positively charged flow-through electrode where contained chloride ions are oxidized to chlorine according to the equation  $2\text{Cl}^- - 2\text{e}^- \rightarrow \text{Cl}_2$  which dissolves in the alkaline solution to form hypochlorite according to the following equation  $\text{Cl}_2 +$



$H_2O \rightarrow Cl^- + H^+ + HOCl$ . The power source to provide the direct electric current for the flow-through electrolytic cell can be, for example, solar cells, wind generators or conventional power grid. The now regenerated lixiviant with pH and hypochlorite content restored, leaves the flow-through electrolytic cell **612** through process line **613** into lixiviant storage tank **615**, thus  
5 completing a closed chemical circuit for the production of uranium. This embodiment is particularly applicable to, for example, the Anderson uranium mine in Yavapai County, Arizona.

Although this embodiment specifically refers to the recovery of uranium by in-situ methods, this is not intended to limit this use of this invention to uranium as numerous other metals such as gold, silver, copper, lead, zinc, or cobalt, to name a few, using appropriate lixiviants that can be  
10 generated or regenerated using a flow-through electrolytic cell of this invention.

FIGURE 17 is a schematic diagram showing one embodiment of this invention whereby treated irrigation water is used to irrigate growing crops. In this diagram, untreated water in pond **701** is pumped through intake line **702** by pump **703** through line **704** into the inter-electrode chamber of flow-through electrolytic cell **705**. In this embodiment, the negatively charged electrode **706** is composed of a conducting wire mesh or screen such as copper or stainless steel, while the  
15 positively charged electrode **707** is a flow-through electrode of graphite felt as depicted in FIGURE 1. The majority of the water passes through electrode **706** where it undergoes reduction by the electrochemical process of decomposing water where  $2H_2O + 2e^- \rightarrow H_2(gas) + 2OH^-$  thereby also increasing the pH of the water. The water becomes saturated in dissolved hydrogen gas. This  
20 water flows through line **708** and either through line **709** to line **711**, or alternatively is stored in storage tank **710** prior to flowing into line **711** and then to a field of irrigated crops **712** where it is used as irrigation water. If storage tank **710** is used, it is preferably made from an electrical non-

conductor such as HDPE, otherwise electrons may flow from the water to the tank. A minority of the feed water in flow-through electrolytic cell **705** flows through the positively charged flow-through electrode **707** where some of the water is oxidized according to the reaction  $2\text{H}_2\text{O} - 4\text{e}^- \rightarrow \text{O}_2(\text{gas}) + 4\text{H}^+$ , thus creating an acidic oxidizing water that may be disposed of, or alternatively,

5 used to control weed growth. The mechanism of controlling flow rate through each electrode can either be controlled by valves (not shown) but normally is self-regulating by the difference in permeability between the open wire mesh or screen of the negative electrode and the tight spacing in the graphite felt of the positive electrode. The graphite felt is preferred due to its resistance to attack by the oxidants generated with the positively charged electrode where metals would rapidly  
10 corrode.

The foregoing discussion of the invention has been presented for purposes of illustration and description. The foregoing is not intended to limit the invention to the form or forms described herein. Although the description of the invention has included description of one or more embodiments, and certain variations and modifications, other verifications and modifications are  
15 within the scope of the invention, e.g., as may be within the skill and knowledge of those in the art, after understanding the preset disclosure. It is intended to obtain rights which include alternative embodiments to the extent permitted, including alternate, interchangeable and/or equivalent structures, functions, ranges or steps to those claimed, whether or not such alternate, interchangeable and/or equivalent structures, functions, ranges or steps are disclosed herein, and  
20 without intending to publicly dedicate any patentable subject matter.